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Hydrological Characteristics in the Catchment Area of Muda and Pedu Reservoirs

— Case study on irrigation management in the Muda Irrigation Scheme, Malaysia —

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Introduction

In the tropical monsoon area, the existence of a reservoir ensuring water supply for the dry season by storing excess water during the wet season is indispensable for rice double cropping. In the Muda Irrigation Scheme, rice double cropping depends very much on the volume of water stored in the Muda and the Pedu Reservoirs. This is especially true for the off-season crop, which relies almost entirely on reservoir water for irrigation. Fig. 1 shows the changes of reservoir storage since 1969. Prior to 1975, the reservoirs were filled to capacity several times. But this has never happened again since double cropping was implemented in more than 90% of the Muda area. In fact, the reservoirs were so depleted that irrigation for the 1978 off-season crop was impossible, and again in 1983 and 1984, only half of the Muda area could be irrigated. Therefore, the shortage of reservoir water remains one of the most serious constraints for the establishment of a stable rice double cropping system. It is thus very important to evaluate the catchment yield of the Muda and the Pedu Reservoirs, and obtain

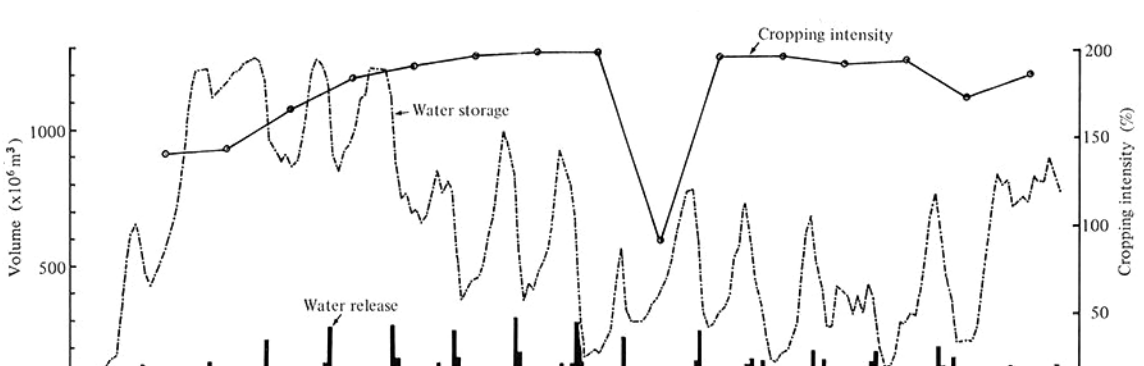

Fig. 1. Changes in water storage and water release from Muda and Pedu Reservoirs together with cropping intensity (1969—1984)

a better understanding of the rainfall-runoff characteristics, so as to formulate better reservoir management strategy.

Under the joint research program between the Muda Agricultural Development Authority (MADA) and the Tropical Agriculture Research Center (TARC) on 'system water management for stable rice double cropping in the Muda Irrigation Scheme', the author had the opportunity to study the rainfall-runoff characteristics in the catchment area of Muda and Pedu Reservoirs covered by primeval tropical forests.

In this paper, the following three approaches were adopted: a) annual rainfall-runoff analysis, b) time series analysis using statistical unit hydrograph method, and c) the b) method which takes seasonal changes into consideration.

For this study, a calendar year is divided into three seasons, i.e., dry (Jan.–Apr.), intermediate (May–Aug.), and wet (Sept.–Dec.).

Study area and data

The study area (1,155.1 km^2) covers the catchment of both the Muda and the Pedu Reservoirs (Fig. 2). The Muda Reservoir (area 25.9 km^2) has a larger catchment area (984.2 km^2) but a smaller storage capacity

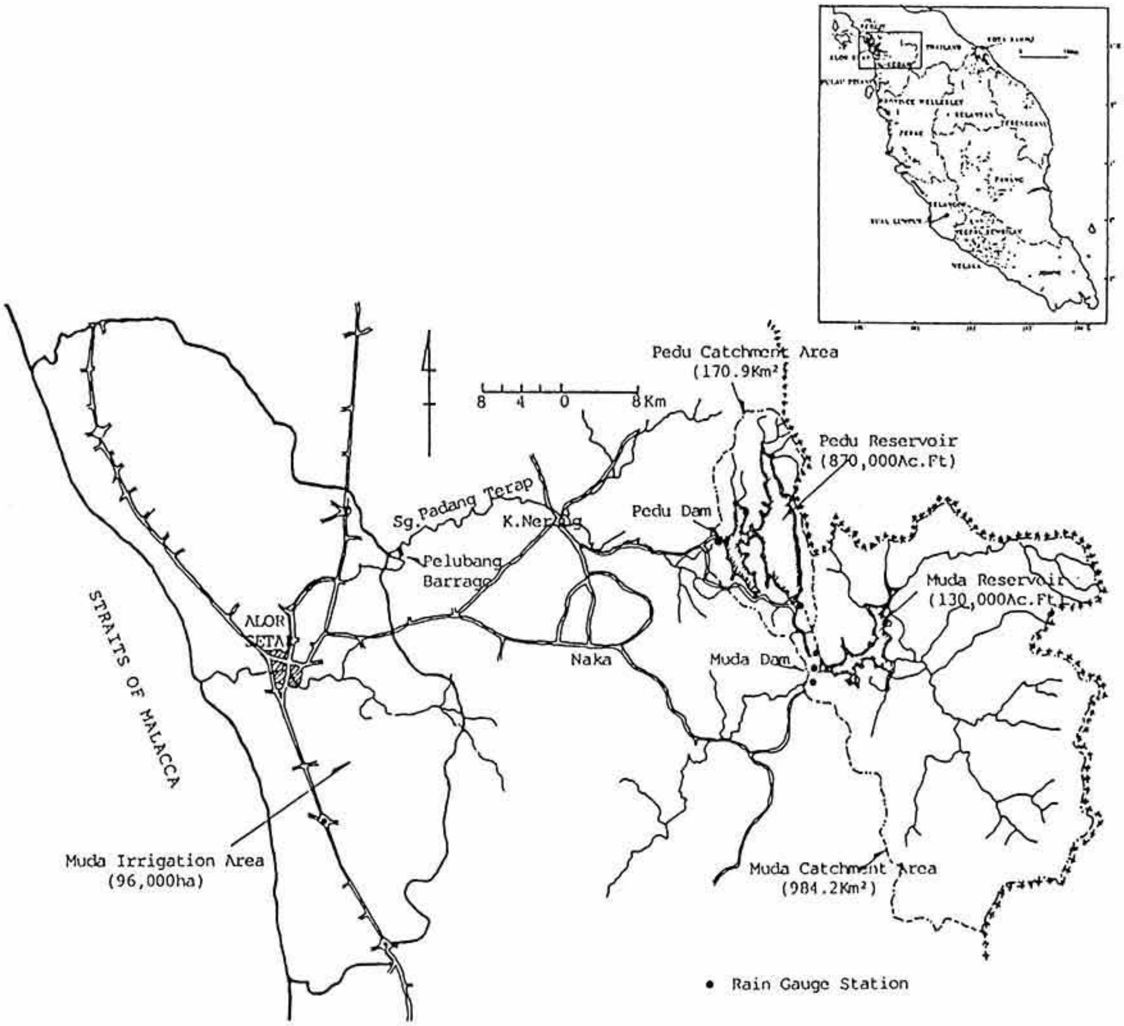

Fig. 2. General plan of Muda Irrigation Scheme

(185×10^6 m^3), while the Pedu Reservoir (area 64.8 km^2) has a smaller catchment area (170.9 km^2) but a larger storage capacity ($1,047\times10^6$ m^3). Water from the Muda Reservoir is channeled to the Pedu Reservoir through the Saiong Tunnel (length 6.6 km), and is released through the Pedu Dam for the irrigation of the Muda Scheme.

The catchment area stretches over both the Kedah-Singgora and the Bintang Ranges (80–1,265 m above sea-level), composed mostly of granite and quartzite rocks, and covered by thick primeval forest.

Water levels in both reservoirs are monitored daily at 7:00 a.m., and the storage volume is read from stage-volume curves which are computed from a topographic map. Five rainfall stations are installed around the dam sites as shown in Fig. 2 to measure the daily rainfall.

For a strict definition of the term "runoff", the following expressions should be used:

$$RU(I)=QIN(I)+E(I)+S(I) -\left(1.0-\frac{RP}{100}\right)R(I)AR(I) \quad\ldots(1)$$

$$QIN(I)=ST(I+1)-ST(I)+QT(I) \ldots(2)$$

where $RU(I)$: actual runoff from the catchment area on day I

$QIN(I)$: net inflow to both reservoirs on day I

$ST(I+1)$: total amount of water stored in both reservoirs at 7:00 a.m. on day $I+1$

$ST(I)$: total amount of water stored in both reservoirs at 7:00 a.m. on day I

$QT(I)$: total outflow from both reservoirs on day I

$E(I)$: evaporation loss from the reservoirs on day I

$S(I)$: seepage loss from the reservoirs on day I

$R(I)$: rainfall in the reservoirs on day I

$AR(I)$: area of reservoirs covered with water on day I

RP : average runoff percentage in the catchment area (%).

However, since only the daily net inflow $QIN(I)$ is actually observed[5], while the other parameters are all unknown, "runoff" will be defined in this paper as equivalent to the net inflow as expressed in Eq. (2).

For the rainfall data, the average value of all five stations was used. It must be noted that since the locations of these stations are not evenly distributed throughout the catchment areas, they may not be able to give accurate and representative rainfall data.

Annual and seasonal rainfall-runoff analyses[2-4]

Using the record of daily rainfall and net inflow data covering a period of 14 years (1971 to 1984), a series of standard analyses of the annual and seasonal rainfall-runoff relationship were carried out. The results are presented as follows:

(1) Fig. 3 shows the relationship between annual rainfall and runoff. Rainfall loss ranges from 1,300 to 1,900 mm/yr, or 3.6 to 5.2 mm/day, for this catchment, as compared to about 500 mm/yr for Japanese catchments[10] where the gradient is steeper and vegetation is thinner. Runoff percentage varies from 20 to 37 with an average of 28, and is of about the same order as that of other rivers in the world[8].

(2) Seasonal rainfall, runoff and runoff percentage are shown in Table 1. Out of the annual mean runoff of 638 mm, dry, intermediate, and wet seasons bring about the seasonal runoff of 110 mm (17%), 159 mm (25%) and 369 mm (58%), respectively.

(3) Each seasonal runoff percentage is shown as follows:

dry season	: 12—60%, average 26%,
intermediate season	: 14—26%, average 19%,
wet season	: 27—46%, average 37%.

During the dry season, the runoff percentage varies widely due to the low proportion of direct runoff and the variable rainfall pattern. In the intermediate season, the runoff percentage becomes minimum due to the reduced base flow associated with the low

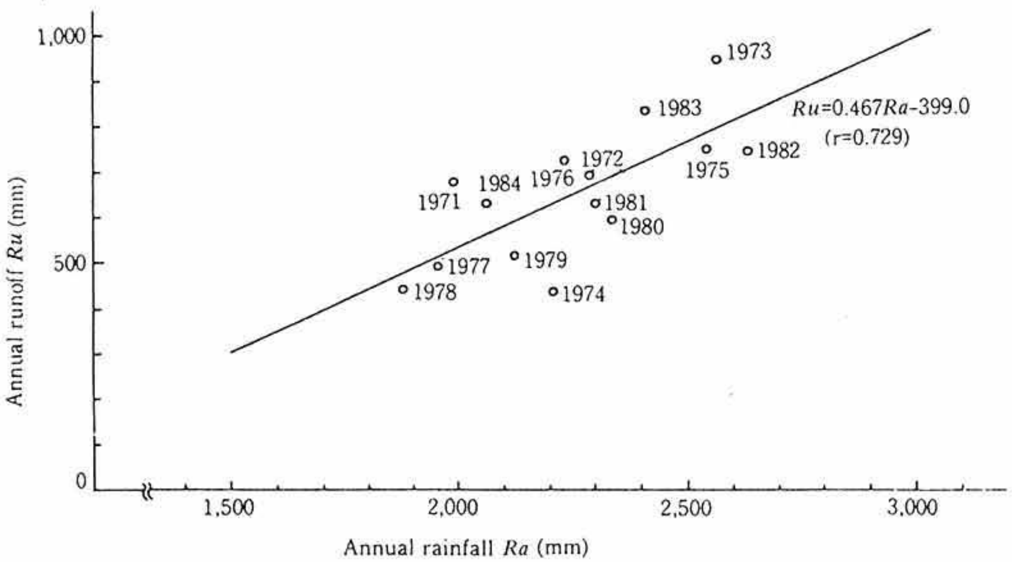

Fig. 3. Relationship between annual rainfall and annual runoff in the catchment area of Muda and Pedu Dams (Muda Irrigation Scheme, Malaysia)

Table 1. Seasonal rainfall, runoff and runoff percentage

Year	Dry season (Jan.-Apr.)			Intermediate season (May-Aug.)			Wet season (Sept.-Dec.)			Annual total		
	Rainfall (mm)	Runoff (mm)	R.P.[1] (%)	Rainfall (mm)	Runoff (mm)	R.P.[1] (%)	Rainfall (mm)	Runoff (mm)	R.P.[1] (%)	Rainfall (mm)	Runoff (mm)	R.P.[1] (%)
1971	360. 6	216. 9	60. 1	656. 8	139. 5	21. 2	986. 5	322. 0	32. 6	2, 004. 0	678. 4	33. 9
1972	528. 4	90. 5	17. 1	426. 8	92. 8	21. 7	1, 329. 0	511. 1	38. 5	2, 284. 3	694. 3	30. 4
1973	483. 0	258. 1	53. 4	1, 052. 1	273. 4	26. 0	1, 026. 3	414. 9	40. 4	2, 561. 4	946. 4	36. 9
1974	427. 8	117. 2	27. 4	827. 1	60. 4	7. 3	953. 9	257. 7	27. 0	2, 208. 9	435. 4	19. 7
1975	555. 3	113. 2	20. 4	939. 6	156. 9	16. 7	1, 048. 7	480. 9	45. 9	2, 543. 6	751. 0	29. 5
1976	363. 3	108. 9	30. 0	891. 4	192. 8	21. 6	953. 9	422. 7	44. 3	2, 208. 9	724. 4	32. 8
1977	174. 3	55. 7	32. 0	816. 5	123. 7	15. 2	965. 1	312. 8	32. 4	1, 955. 8	492. 2	25. 2
1978	341. 2	55. 9	16. 4	722. 4	121. 1	16. 8	813. 0	263. 8	32. 4	1, 876. 7	440. 8	23. 5
1979	410. 2	49. 8	12. 1	833. 7	161. 1	19. 3	881. 5	305. 3	34. 6	2, 125. 4	516. 2	24. 3
1980	385. 3	56. 1	14. 6	936. 9	130. 4	13. 9	1, 016. 2	409. 9	40. 3	2, 338. 3	596. 4	25. 5
1981	429. 8	89. 1	20. 7	953. 1	245. 4	25. 7	916. 3	301. 7	32. 9	2, 299. 2	636. 2	27. 7
1982	630. 3	109. 4	17. 4	895. 4	214. 2	23. 9	1, 102. 8	423. 4	38. 4	2, 628. 5	746. 9	28. 7
Mean	424. 1	110. 1	26. 0	829. 3	159. 3	19. 2	999. 4	368. 9	36. 9	2, 252. 9	638. 2	28. 3

1) : Runoff percentage$=\frac{\text{Runoff}}{\text{Rainfall}}\times 100(\%)$.

precipitation during the preceding dry season, and the low direct runoff percentage as an infiltration capacity is still high in the catchment area. The runoff percentage becomes maximum in the wet season due to high direct runoff. The net runoff during the wet season accounts for more than 50% of the annual runoff.

(4) It is recognized that the runoff percentage is in inverse proportion to rainfall in the dry season. However, in the intermediate and the wet seasons, the relation becomes positive. Especially, the regression coefficient between rainfall and runoff percentage becomes maximum in the wet season. It is possible to consider that the gradient of

the regression line reflects the sensitivity of the response of direct runoff to rainfall. The negative regression coefficient in the dry season is caused by the small proportion of direct runoff to base flow.

On the other hand, it is known that water infiltration into dry soil (at pF higher than 3.0) decreases due to increased water repellency of the dry soil[7]. Studies have to be done to examine whether this phenomenon influences water runoff in the catchments during the dry season or not.

(5) Fig. 4 shows the exceedance probability plot of annual runoff (equivalent to net inflow by definition). This is compared to the estimated annual runoff (net inflow) outlined in the Feasibility Report for the Muda Scheme[6]. In a "normal" year (with exceedance probability of 50%), the actual annual runoff from the catchments is only 740 million cubic meter or 640.7 mm depth, as against the designed value of 925 million cubic meter or 800.9 mm depth, both of which are about 20% lower. This indicates a much more serious situation

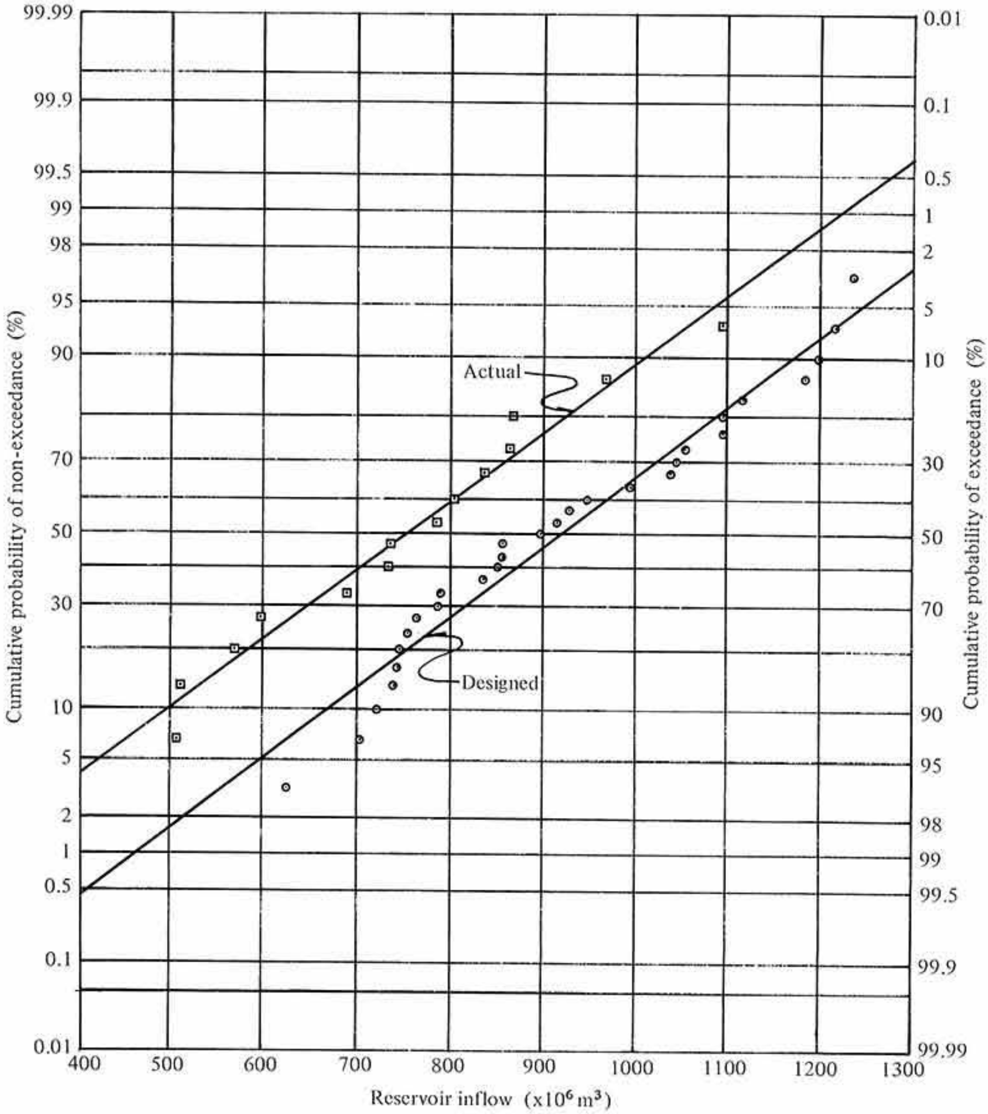

Fig. 4. Exceedance probability of reservoir inflow, Muda and Pedu Dams, Malaysia

than that anticipated in the Feasibility Report for the scheme, in the possibility of failure to meet the water demand.

(6) Based on the relationship of mean monthly rainfall and runoff, an interesting observation is that runoff seems to lag behind rainfall over about three months.

Time series analysis of rainfall-runoff relationship[2-4]

1) Method of analysis

Several methods are commonly used for the time series analysis of rainfall-runoff. Here, the statistical unit hydrograph method was chosen. This statistical method is based on the assumption that rainfall and runoff can be considered respectively as the input and output of a black box, and their relationship is a linear system, which can be expressed by the impulse response function series called the convolution integral as follows[1]:

$$ru(t)=\int_{-\infty}^{t} h(t-\tau)r(\tau)d\tau+h_0 \quad \cdots\cdots\cdots\cdots\cdots(3)$$

or

$$ru(t)=\int_{0}^{\infty} h(\tau)r(t-\tau)d\tau+h_0 \quad \cdots\cdots\cdots\cdots\cdots(4)$$

where $ru(t)$: time series of runoff from the catchment area (mm)
$r(t)$: time series of rainfall in the catchment area (mm)
$h(\tau)$: runoff kernel, i.e., statistical unit hydrograph
τ : time-lag
h_0 : constant

Eq. (3) can be represented by the following linear multiple regression model.

$$ru(t)=\alpha_0+\sum_{i=1}^{L}\alpha_i r_i(t)+\varepsilon \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots(5)$$

where α_0, α_i : partial regression coefficients, which are all unknown parameters
$r_i(t)$: rainfall (mm)
suffix i means that the lag from time t is $(i-1)$, i.e., $r_i(t)=r(t-i+1)$
L : maximum time-lag
ε : residual

The optimum unbiased estimates of α_0 and α_i can be obtained by the least square method.

Representing optimum unbiased estimates of α_0 and α_i by partial regression coefficients a_0 and a_i respectively, Eq. (5) can be converted as follows:

$$Ru(t)=a_0+\sum_{i=1}^{L}a_i r(t-i+1) \quad \cdots\cdots\cdots\cdots\cdots\cdots(6)$$

where $Ru(t)$: statistically estimated runoff (mm)

In deriving the multiple regression model, it is necessary and very important to determine the maximum time-lag (L). As it is not practical to consider infinite (∞) maximum time-lag (L), L should be given a finite and adequate value. The following criteria may be used to determine L:

(1) Time-lag should be as long as possible for better approximation.

(2) As the actual data series is finite, it is not practical to apply unreasonably long time-lag.

(3) It is necessary that the partial regression coefficients a_0 and a_i $(i=1\text{–}L)$ are positive.

However, in this paper, a_0 was allowed to be negative for the following reason. The constant a_0 generally refers to the base flow in Eq. (6), but due to the definition of runoff as equivalent to the net inflow to the reservoirs, a_0 represents the component of seepage and evaporation losses from the reservoirs as well as base flow. Therefore, it is quite possible that a_0 becomes negative.

(4) It is necessary to evaluate the multiple regression model by employing criteria, such as multiple correlation coefficient and analysis of variance.

(5) In order to obtain reliable partial regression coefficients in the multiple regression model, it is necessary that the predictor variables are statistically independent of each other. The autocorrelation coefficients can be employed

Table 2. Multiple regression models for runoff in the catchment area of Muda and Pedu Dams, Malaysia

Items	Equations	MCC[1]	Variables
Monthly runoff	$Ru(t)=-25.105+0.225r(t)+0.072r(t-1)+0.122r(t-2)$ ……(7)	0.780	$Ru(t)$: estimated runoff during the one-month period t (mm) $r(t-i)$: actual rainfall during the one-month period $t-i$(mm) ($i=0, 1, 2$)
10-day runoff	$Ru(t)=-10.921+0.200r(t)+0.047r(t-1)+0.041r(t-2)$ $+0.018r(t-3)+0.013r(t-4)+0.029r(t-5)$ $+0.032r(t-6)+0.032r(t-7)+0.044r(t-8)$ ……(8)	0.786	$Ru(t)$: estimated runoff for a period of 10-day t(mm) $r(t-i)$: actual rainfall for a period of 10-day $t-i$ (mm) ($i=0, 1, 2, \cdots 8$)
5-day runoff	$Ru(t)=-5.206+0.164r(t)+0.066r(t-1)+0.014r(t-2)$ $+0.012r(t-3)+0.019r(t-4)+0.014r(t-5)$ $+0.008r(t-6)+0.011r(t-7)+0.001r(t-8)$ $+0.023r(t-9)+0.014r(t-10)+0.010r(t-11)$ $+0.004r(t-12)+0.028r(t-13)+0.020r(t-14)$ $+0.013r(t-15)+0.027r(t-16)$ ……(9)	0.766	$Ru(t)$: estimated runoff for a period of 5-day t(mm) $r(t-i)$: actual rainfall for a period of 5-day $t-i$(mm) ($i=0, 1, 2, \cdots 16$)
Daily runoff	$Ru(t)=-0.1829+0.09727r(t)+0.06308r(t-1)+0.02087r(t-2)$ $+0.01152r(t-3)+0.01062r(t-4)+0.00843r(t-5)$ $+0.00819r(t-6)+0.00698r(t-7)+0.00355r(t-8)$ $+0.00473r(t-9)+0.00330r(t-10)+0.00361r(t-11)$ $+0.00595r(t-12)+0.00414r(t-13)+0.00012r(t-14)$ $+0.00054r(t-15)+0.00110r(t-16)+0.00581r(t-17)$ $+0.00674r(t-18)+0.00543r(t-19)+0.00276r(t-20)$ $+0.00536r(t-21)+0.00581r(t-22)+0.00275r(t-23)$ $+0.00653r(t-24)+0.00742r(t-25)+0.00732r(t-26)$ ……(10)	0.700	$Ru(t)$: estimated runoff on day t(mm) $r(t-i)$: actual rainfall on day $t-i$(mm) ($i=0, 1, 2, \cdots 26$)

[1] : Multiple correlation coefficient.

to examine the independency of the rainfall sequence.

2) Results of analysis

Using 12-year data, a series of time series analyses were carried out. The results are presented as follows:

(1) Time series analysis was carried out without considering seasonality throughout 12 years (14 years for monthly rainfall-runoff analysis) on a monthly, 10-day, 5-day and daily basis. The multiple regression equations (7)–(10) in Table 2 were derived.

(2) Based on the results of the daily rainfall-runoff analysis carried out by using a multiple regression model in each season, it is possible to identify the seasonal runoff characteristics (Figs. 5(a)–5(c)).

The total of partial regression coefficient $\sum_{i=1}^{L} a_i$ expresses the total linear runoff percentage, i.e., direct runoff percentage. Therefore, by comparing $\sum_{i=1}^{L} a_i$, the importance of direct runoff can be estimated in each season. $\sum_{i=1}^{L} a_i$ becomes increasingly larger in the order of dry season (average 0.127), intermediate

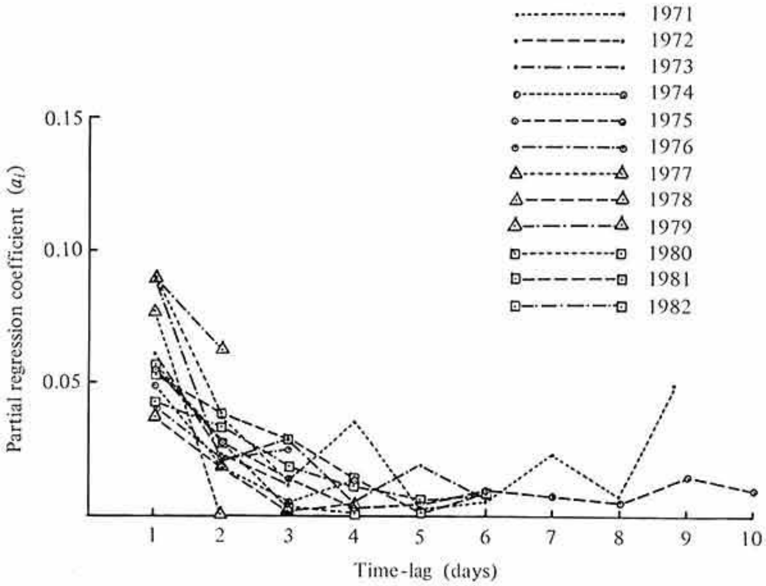

Fig. 5(a). Statistical unit hydrograph during the dry season (Jan.-Apr.) Catchment area of Muda and Pedu Reservoirs: 1971—1982.

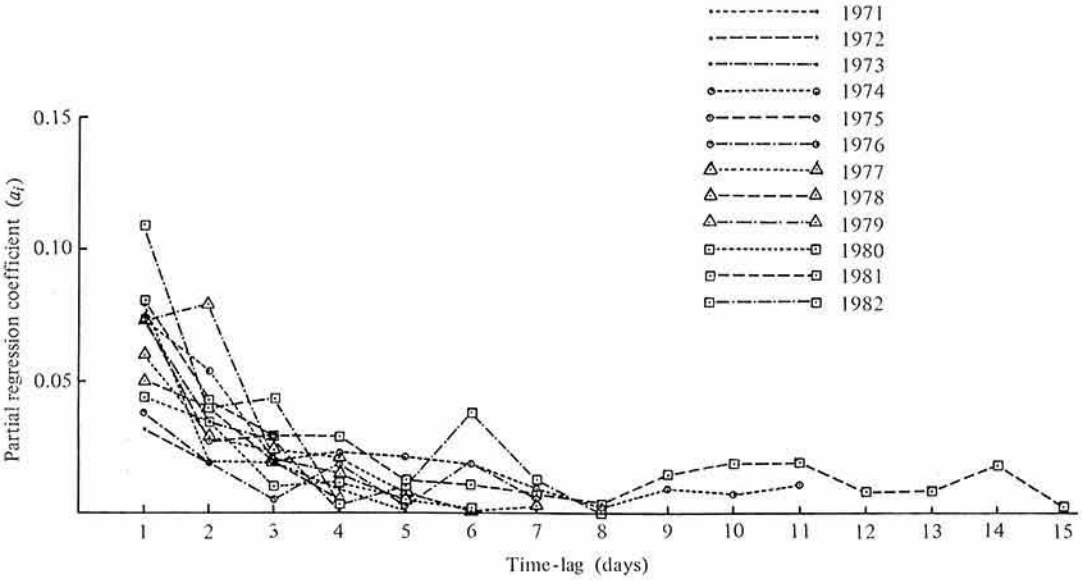

Fig. 5(b). Statistical unit hydrograph during the intermediate season (May-Aug.) Catchment area of Muda and Pedu Reservoirs: 1971—1982.

season (average 0.160) and wet season (average 0.317).

(3) Modifying three sets of original equations obtained in the process of the analyses mentioned in (1) and (2) so as to fit the estimated data to the observed data in each season, the three rainfall-runoff models were constructed and altogether 9 runoff estima-

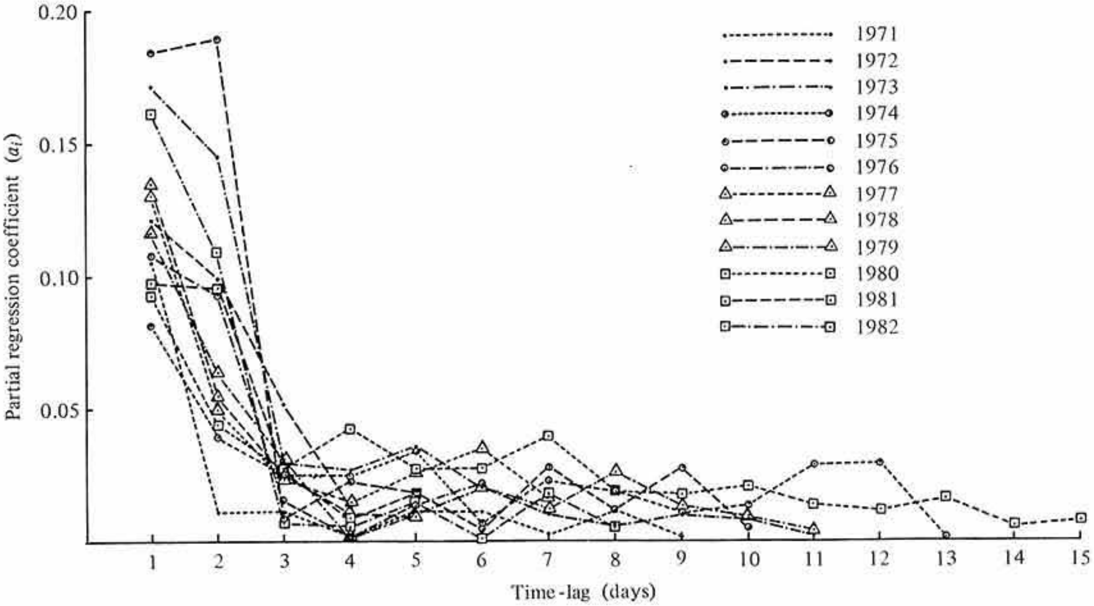

Fig. 5(c). Statistical unit hydrograph during the wet season (Sept. -Dec.) Catchment area of Muda and Pedu Reservoirs: 1971—1982.

tion equations were obtained. It appears that all the models expresses adequately the seasonality of rainfall-runoff characteristics. Here, only Model I is shown as follows. Correlation coefficient (R), standard error of estimate (S) and coefficient of variation (V) for the modified equations are shown together with those of the original equations in parenthesis.

[Model I]: modified runoff estimation equations corresponding to Eq. (10)

① Dry season (Jan.–Apr.)

$$\begin{aligned} Ru(t)=\ &0.28853+0.05659r(t)\\ &+0.03670r(t-1)+0.01214r(t-2)\\ &+0.00670r(t-3)+0.00618r(t-4)\\ &+0.00490r(t-5)+0.00477r(t-6)\\ &+0.00406r(t-7)+0.00207r(t-8)\\ &+0.00275r(t-9)+0.00192r(t-10)\\ &+0.00021r(t-11)+0.00346r(t-12)\\ &+0.00256r(t-13)+0.00007r(t-14)\\ &+0.00031r(t-15)+0.00064r(t-16)\\ &+0.00338r(t-17)+0.00392r(t-18)\\ &+0.00316r(t-19)+0.00161r(t-20)\\ &+0.00312r(t-21)+0.00338r(t-22)\\ &+0.00160r(t-23)+0.00380r(t-24)\\ &+0.00432r(t-25)+0.00426r(t-26)\\ &\cdots\cdots\cdots\cdots\cdots\cdots(11\,\mathrm{a}) \end{aligned}$$

$R=0.536(0.536)$
$S=1.252(1.377)$
$V=1.433(1.576)$

② Intermediate season (May–Aug.)

$$\begin{aligned} Ru(t)=\ &-0.24823+0.07053r(t)\\ &+0.04574r(t-1)+0.01513r(t-2)\\ &+0.00835r(t-3)+0.00770r(t-4)\\ &+0.00611r(t-5)+0.00594r(t-6)\\ &+0.00506r(t-7)+0.00258r(t-8)\\ &+0.00343r(t-9)+0.00239r(t-10)\\ &+0.00262r(t-11)+0.00432r(t-12)\\ &+0.00319r(t-13)+0.00009r(t-14)\\ &+0.00039r(t-15)+0.00080r(t-16)\\ &+0.00421r(t-17)+0.00489r(t-18)\\ &+0.00394r(t-19)+0.00200r(t-20)\\ &+0.00388r(t-21)+0.00422r(t-22)\\ &+0.00199r(t-23)+0.00473r(t-24)\\ &+0.00538r(t-25)+0.00531r(t-26)\\ &\cdots\cdots\cdots\cdots\cdots\cdots(11\,\mathrm{b}) \end{aligned}$$

$R=0.671(0.671)$
$S=1.212(1.437)$
$V=0.936(1.110)$

③ Wet season (Sept.-Dec.)

$$\begin{aligned} Ru(t)=\ &-0.50630+0.13225r(t)\\ &+0.08577r(t-1)+0.02838r(t-2) \end{aligned}$$

$$\begin{aligned}
&+0.01567r(t-3)+0.01444r(t-4)\\
&+0.01146r(t-5)+0.01114r(t-6)\\
&+0.00949r(t-7)+0.00483r(t-8)\\
&+0.00643r(t-9)+0.00448r(t-10)\\
&+0.00491r(t-11)+0.00809r(t-12)\\
&+0.00599r(t-13)+0.00017r(t-14)\\
&+0.00073r(t-15)+0.00149r(t-16)\\
&+0.00790r(t-17)+0.00917r(t-18)\\
&+0.00739r(t-19)+0.00376r(t-20)\\
&+0.00728r(t-21)+0.00791r(t-22)\\
&+0.00374r(t-23)+0.00888r(t-24)\\
&+0.01009r(t-25)+0.00995r(t-26)\\
&\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(11\text{c})
\end{aligned}$$

$R=0.762(0.762)$
$S=2.069(2.252)$
$V=0.684(0.744)$

Considering the data covering a 12-year period (1971–1982), Eqs. (11a), (11b) and (11c) give an estimate of which R, S and V are as follows:

$R=0.766(0.700)$
$S=1.564(1.738)$
$V=0.900(1.000)$

Seasonal statistical unit hydrographs for Models II and III are shown in Figs. 6 and 7.

Conclusions and recommendations

The analysis carried out in this section is based on the mean value of rainfall of five stations which are installed around the dam sites only. Thus it is desirable to set up a large number of rainfall stations inside the catchment area to improve the analysis further.

Based on the annual rainfall-runoff analysis, it became clear that the water demand in the Muda area cannot be met by the runoff from the catchment alone. Therefore, in order to cover the water deficit, it is strongly recommended to adopt every measure available, such as recycling of water, effective use of uncontrolled river flow and rainfall, improved field water management, etc.

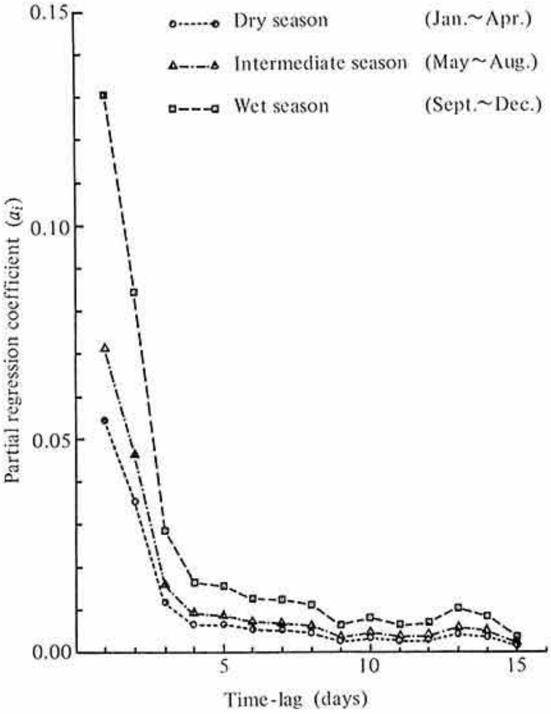

Fig. 6. Statistical unit hydrograph (Model II), catchment area of Muda and Pedu Reservoirs

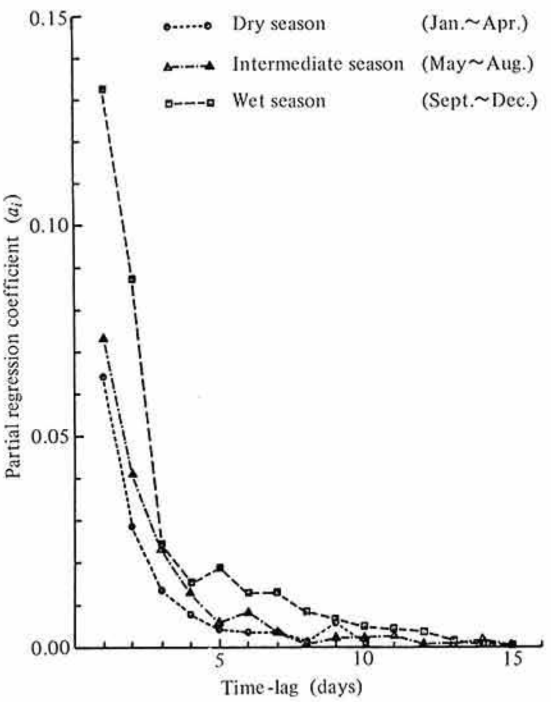

Fig. 7. Statistical unit hydrograph (Model III), catchment area of Muda and Pedu Reservoirs

It may be considered that deforestation would increase the runoff percentage in the catchment area and improve the water supply and demand relation in the Muda Scheme. However, deforestation would result in an increased frequency of flood and would provide silting in the two reservoirs as well as the destruction of the ecosystems in the catchment area. The tropical forests in the catchment area should be preserved in their totality.

It was reported that induced artificial rain (cloud seeding) had been able to alleviate drought in the past. However, as the runoff percentage is about 28% only, this method would have a limited effect on the alleviation of drought. Therefore, artificial rain should be induced in the irrigation area rather than in the catchment area.

In the time series analysis of the rainfall-runoff relationship, four multiple regression equations, of which the criterion variable is runoff and predictor variable is rainfall for the specified periods of one month, 10-day, 5-day and 1-day, were derived under the assumption that the rainfall-runoff relation is linear throughout the year. These equations can be used for the setting of the water release schedule of the reservoirs.

However, for the daily runoff estimation, it is desirable to apply the multiple regression models obtained by taking into account the seasonality of the runoff characteristics. In choosing one model out of these three, both accuracy and simplicity which depend on the purpose of application should be considered.

In adopting the runoff equations (models), it is necessary to keep in mind that these were obtained from the irrigation point of view.

For further analysis, it is necessary to determine the limit for the adoption of the linear prediction by taking into account the Fixed Maximum Rainfall (F.M.R.) or the Fixed Maximum Discharge (F.M.D.)[9]. However, it seems meaningless to introduce non-linear analysis under the current accuracy of existing rainfall and runoff data. It is strongly recommended for non-linear analysis and flood runoff analysis to incorporate the entire observation system of rainfall and runoff into a reliable system based on hourly-observation.

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